RESTORATION SUCCESS OF THE SANTA CRUZ RIVER HERITAGE PROJECT: A REMOTE SENSING ANALYSIS OF RECYCLED URBAN WATER IMPACTS, TUCSON, ARIZONA

by

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ABSTRACT

Arid rivers around the world are undergoing rapid hydrological and ecological change due to urbanization, groundwater depletion, and climate pressures. In response to these pressures, the Santa Cruz River Heritage Project (SCRHP) in Tucson, Arizona, reintroduced recycled urban water to restore base streamflow and promote ecological recovery. My study evaluated whether measurable ecological change, specifically in land cover and vegetation, occurred between 2018 and 2023 along the downstream reach influenced by the SCRHP. Using remote sensing tools in QGIS, National Land Cover Database (NLCD) data, confusion matrices, and high-resolution National Agricultural Imagery Program (NAIP) imagery, I compared changes in land cover classification over time for areas around the impacted downstream reach and an upstream control reach of the Santa Cruz River. Losses in vegetation and wetland areas were suggested by NLCD data alone, but high-resolution imagery and error analysis indicated that some of these changes reflected misclassification rather than true ecological change. Although NLCD data detect broad trends, they underestimate fine-scale changes along narrow riparian areas that are critical to evaluate restoration success. These findings highlight the importance of pairing coarse and high-resolution datasets, field validation, and long-term monitoring to more accurately assess restoration outcomes in dynamic arid river systems.

INTRODUCTION

Background

Rivers around the world are dynamic systems undergoing vast transformation. Rivers are changing at a rapid pace, especially those of arid ecosystems (Wu et al. 2023). These changes are brought on by several factors, including human intervention (Wohl 2019), increased demand for water (Sabater et al. 2018), and climate change (Wang et al. 2021). River ecosystems provide critical ecological and social benefits but are increasingly threatened by hydrological modification (Sabater and Tockner 2009), biodiversity loss (Sayer et al. 2025), and degradation of ecosystem services (Li et al. 2022a).

The Santa Cruz River (Figure 1) in Southern Arizona exemplifies these changes. Historically a perennial river supporting rich riparian habitats (Betancourt 1990), it has experienced severe degradation over the past century due to urban expansion, groundwater depletion, and altered hydrology (Eastoe and Gu 2016). Restoration efforts, such as the Santa Cruz River Heritage Project (SCRHP), have reintroduced recycled urban water to help restore the river's ecological functions and ecosystem services (Wildermuth and Conrad 2023). However, the long-term effectiveness of these interventions remains unclear. Therefore, my study examines the ecological effects of these restoration interventions on riparian landcover dynamics.



Figure 1. Southcentral Arizona showing the extent of the north-flowing Santa Cruz River. *Created by Colin Seebach, using QGIS.*

Impacts of Changing Rivers

Changes in river systems lead to ecological and socio-economic impacts. Hydrological modifications can alter flow regimes, disrupt aquatic and riparian ecosystems, and jeopardize ecosystem services (Sabater et al. 2018). The Colorado River, for example, has experienced alteration to its flow due to extensive damming and water diversion, resulting in reduced sediment transport and natural flood cycles (Olden and Naiman 2010). These changes have had an impact on the river's riparian habitats and the native fish populations (Olden and Naiman 2010). Similarly, in the Yellow River in China, frequent loss of surface water in its lower reaches and a reduction in wetland areas have been observed as a result of damming and human water usage (Jiongxin 2004). Loss of wetlands is of further concern, as the wetlands support diverse

bird populations (Jiongxin 2004). Both aquatic and the surrounding riparian ecosystems are disrupted by changes to hydrology. For example, in the Murray-Darling Basin of Australia, increased water extraction led to threatened endemic fish and riparian vegetation (Kingsford 2000). Lastly, compromised ecosystem services are a major concern of changed rivers. The Aral Sea Basin of Central Asia and the Ganges River of India have seen increasingly saline water and soil and poor water quality which have caused the collapse of fisheries, decreased agricultural yields, and declining human health (Micklin 2007, Vorosmarty et al. 2010).

Hydrological modification is being observed in many areas of the world, but arid-zone rivers are particularly vulnerable, with concerns of habitat loss, decline in biodiversity, and changing hydrological patterns (Jenkins and Boulton 2007, Larned et al. 2010, Wohl et al. 2015). Intermittent flow regimes, which are very common for desert rivers, compound these challenges by creating unpredictable and unstable ecological conditions (Datry et al. 2014, Ekka et al. 2020). These conditions, such as high variability in water availability, can lead to extended dry periods, disrupting life cycles of aquatic organisms, reducing habitat connectivity, and disrupting biogeochemical cycles (Datry et al. 2014, Gerhard et al. 2023). Given the vulnerability of river ecosystems in arid zones to hydrological modifications, restoration efforts are essential to mitigate ecological degradation and to sustain important ecosystem functions in these regions.

Importance of River Restoration in Arid Regions

River restoration is an area of management that has many benefits. River restoration, in many cases, is crucial for maintaining and stabilizing ecosystem functions and services, particularly where water availability is variable and natural hydrological processes have been altered. Restoration efforts aim to enhance biodiversity, improve habitat quality, and increase

water sustainability. In turn, these efforts can work towards regaining full potential for the ecological, biogeochemical, and hydrogeomorphic processes that are needed for the ecosystem functions and services (Palmer et al. 2014). Additionally, by improving habitat conditions for flora and fauna, restoration can help support native species and promote ecological resilience in degraded river systems (Li et al. 2022b).

Because of the unique conditions of arid regions, such as high evapotranspiration rates, and inconsistent flow, limited water availability, and socio-ecological competition for the limited available water, river restoration in these areas has many challenges. Some of the key principles of river restoration in arid regions are meant to address these challenges. A focus on restoring consistent flow regimes, establishing drought-tolerant plant species, and reducing channel incision and bank erosion helps to address these challenges (Beechie et al. 2010, Gurnell 2014, Wohl et al. 2015).

Role of Recycled Urban Water in River Restoration

Restoration projects in urban arid regions often incorporate recycled urban water to reintroduce flow and support vegetation recovery (Wildermuth and Conrad 2023, Wohl et al. 2024). Recycled urban water – also referred to as treated municipal effluent – is wastewater that has undergone multiple stages of treatment (Hobbs and Cramer 2008). The treatment typically includes several stages of filtration that remove organic matter, nutrients, pathogens, and contaminants, bringing it to levels suitable for discharge or reuse. The water must meet regional regulations and standards for nutrients, suspended solids, and microbial content before it is released into natural waterways or used for environmental (Hobbs and Cramer 2008). The introduction of recycled water often results in ecosystems with novel species assemblages.

Although, these systems may not replicate historical ecosystems, they can reestablish ecological function, support biodiversity, and offer long-term resilience in water-limited environments (Hobbs et al. 2006).

The reintroduction of water is successful for several reasons. First, the additional water supplements the streamflow, which reduces dry periods. The additional water also promotes groundwater recharge, which helps to sustain water table levels. Finally, vegetation recovery is also supported by the additional water, allowing riparian plant communities to thrive and increase habitat quality for consumers as well (Bischel et al. 2013).

Successful river restoration through the incorporation of recycled urban water has been observed in several cases, with many benefits being realized. For example, a restoration project used sewage effluent to create wetlands along the Rio Grande in North America. The efforts benefited migratory birds, native flora and fauna, and the local communities (Landis 2012). Another successful case includes the reintroduction of treated water to the Los Angeles River in California. In this case, the use of effluent water has had a long history of supporting freshwater marshlands, fish migration, shorebird habitat, riparian habitat, and recreation (Wolfand et al. 2022).

Role of Remote Sensing in River Restoration Assessment

Geographic Information Systems (GIS) are remote sensing tools that can be used for capturing, analyzing, and visualizing spatial data (Vine et al. 1997). GIS tools allow researchers and managers to analyze patterns, trends, and relationships across space and time (Hoang Tu et al. 2023). Although it is used in many fields, GIS-based analysis is often used in environmental

applications by monitoring land cover change, assessing ecosystem health, and informing management of natural resources (Hoang Tu et al. 2023).

For river restoration projects, GIS-based remote sensing tools have proven to be extremely useful and can be applied in many ways. Some examples of its utility are that it has been used to aid in the design of riparian buffer strips within agricultural watersheds (Gu and Liu 2010) to inform decision-making as to which areas to focus on for restoration (Russell et al. 2008). Remote sensing strategies have also been used to analyze the success of wetlands restoration after some river management practices were implemented (Dong et al. 2014).

This project will make special use of GIS-based remote sensing tools that can track land cover change. GIS-based remote sensing tools enable researchers to compare historical and current land cover. By analyzing satellite imagery along a river corridor, changes in riparian vegetation, water extent, and bare ground can all be quantified. GIS-based remote sensing analysis can also help to measure species or stratum composition, which can be helpful to determine the extent of change over space and time.

Although GIS-based remote sensing techniques are valuable for assessing river restoration worldwide, its application may be particularly crucial in arid environments where water availability has a particularly tight link with ecosystem health. One such system is the Santa Cruz River, a historically important yet heavily altered waterway in the Sonoran Desert of North America. Understanding how its hydrology and the riparian landscapes that it supports have changed over time provides insight into the challenges and opportunities for restoration in this fragile ecosystem.

Knowledge Gap and Research Questions

The Santa Cruz River Heritage Project, the managed restoration effort to incorporate recycled urban water from the city of Tucson back into the Santa Cruz River, aligns with the practices of these other restoration projects (Wohl et al. 2024). However, despite the need for continuous monitoring and adaptation, the long-term ecological success of this project, in terms of land cover change and vegetation, has not been adequately assessed. Understanding the impacts on vegetation and land cover of incorporating recycled urban water into the Santa Cruz River is essential for developing and evaluating effective conservation strategies. This understanding is also essential for guiding future restoration efforts in similar situations and environments.

Statement and Objectives

The Santa Cruz River Heritage Project represents an effort to restore ecological integrity to a historically degraded river using recycled urban water. While the strategy of restoring surface flow by returning recycled urban wastewater to a river channel has been implemented in other arid regions, the long-term ecological success of the Santa Cruz River restoration has not been assessed with coarse spatial metrics. Specifically, there is a lack of research evaluating how land cover and vegetation stratum (shrubland, forest, and wetlands) along the river channel have changed since implementing a river restoration project involving the introduction of recycled urban water.

My study aims to assess the extent of land cover change along the Santa Cruz River by analyzing land cover changes using remote sensing spatial analysis. Statistically significant gains of acreage of water and/or vegetation land cover will be considered successful. The use of GIS-

based remote sensing analysis allows for a systematic, scalable, and quantitative assessment of changes in vegetation and habitat conditions over time.

To evaluate the ecological success of the Santa Cruz River restoration, my study will address the following questions:

1. How has land cover changed along the restored reach of the Santa Cruz River since the implementation of the Santa Cruz River Heritage Project?
2. To what extent has riparian vegetation responded to the reintroduction of surface flows from recycled urban water?
3. What insights can GIS-based remote sensing analysis provide about the spatial and temporal patterns of ecological restoration in an arid river system?

METHODOLOGY

Study Area

The Santa Cruz River (see Figure 1), located in southern Arizona, is a north-flowing river that originates in southeastern Arizona, flows south into Mexico, and reenters the United States near Nogales before continuing north through Tucson towards Casa Grande (Wildermuth and Conrad 2023). The Santa Cruz River had, historically, been a perennial river that supported lush and thriving riparian habitats and served as an essential source of water for the indigenous groups, such as the Tohono O'odham (Betancourt 1990). The Tohono O'odham people relied on its cienegas, a unique type of riparian wetlands found in arid ecosystems, to grow crops and allow them to settle (Betancourt 1990).

In more recent time, the Santa Cruz River and its watershed have experienced many changes. During European colonization, irrigation systems were put in place to support

agriculture. A dam was also added in the late 1800s to create what was known as Warner's Lake, a lake that has long since been drained due to increased groundwater extraction (Betancourt 1990). Over the past two centuries, the changes in hydrology have affected the river's natural flow (Arizona Department of Water Resources 2025). These changes have resulted in a transformation from a lush riparian corridor to the ephemeral waterway that we see today. Now, water flow is only observed during seasonal occurrences, such as monsoons, or downstream from the outfall point of the current recycled urban water project (Wildermuth and Conrad 2023, Arizona Department of Water Resources 2025, U.S. Geological Survey 2025).

The changes to hydrology within the Santa Cruz River watershed are a result of management and urbanization challenges. The expansion of Tucson has led to a widespread increase in groundwater pumping, causing a steep decline in the water table level and the subsequent loss of perennial flow to all reaches of the river (Wildermuth and Conrad 2023, Arizona Department of Water Resources 2025, U.S. Geological Survey 2025). The changing climate and increased evapotranspiration rates have made the challenge of water retention and aquifer recharge increasingly difficult (Wildermuth and Conrad 2023).

As a result of the hydrological changes, the Santa Cruz River has also seen negative ecological effects. Habitat degradation and loss, as well as shifts in vegetation communities, have all been observed (Wildermuth and Conrad 2023). Historically, mesquite bosques and cottonwood-willow forests, which are crucial habitats for wildlife, were supported along the river corridor (Betancourt 1990, Wildermuth and Conrad 2023). The reduced flow and groundwater depletion, however, have resulted in the loss of much vegetation and increased channel incision (Eastoe and Gu 2016). These impacts have a negative effect on the river's ability to support native species.

In response to these challenges and ecological degradation, the Santa Cruz River Heritage Project, a managed recharge project, has been implemented beginning in June of 2019, and introduces treated wastewater into the river channel in Tucson, restoring base streamflow (Wildermuth and Conrad 2023). To be proximal to the water treatment plant, the outfall site was chosen to be located east of downtown Tucson (Figure 2). The major goals of the SCRHP in restoring flow to the river are to restore riparian wetlands, mesquite bosques, and cottonwood-willow forests within and along the river channel (Wildermuth and Conrad 2023). These changes will improve the ecosystem services provided by the Santa Cruz River ecosystem (Luthy et al. 2015). However, the challenge of balancing urban water demands, and ecological restoration efforts remains, and such continued monitoring and adaptation are required.

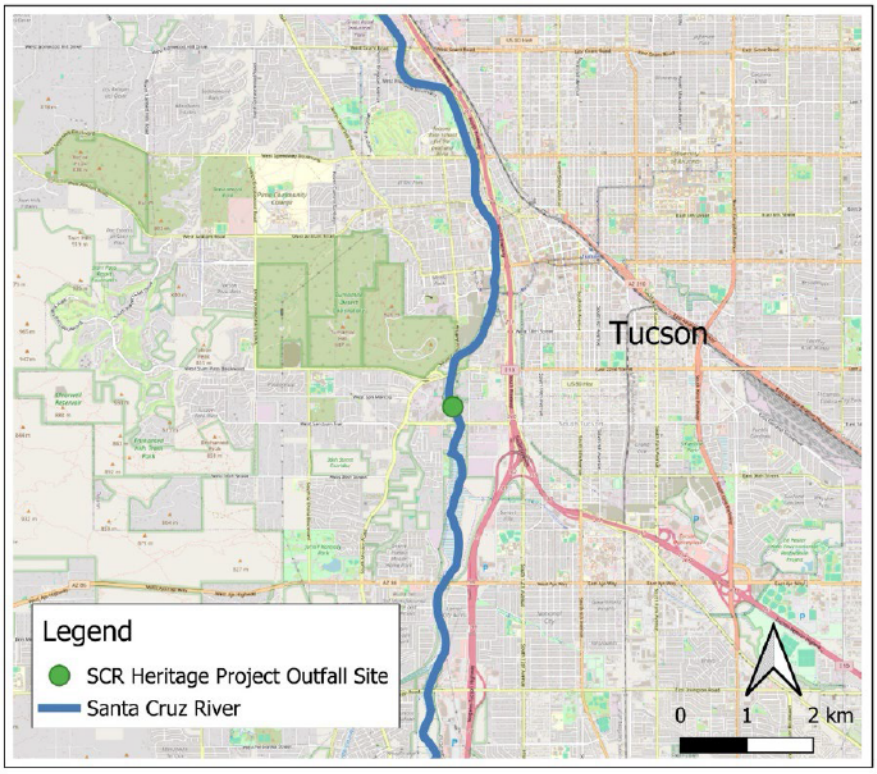


Figure 2. Santa Cruz River in Tucson, with the green marker at Heritage Project Outfall Site. *Created by Colin Seebach, using QGIS.*

My study was conducted along the Santa Cruz River in southern Arizona, focusing on the reach impacted by the Santa Cruz River Heritage Project (SCRHP) (Figure 3). Initiated in June 2019, the SCRHP introduced treated wastewater into the river channel within Tucson to restore base streamflow and improve riparian ecosystems. The geographic scope of this study extends from the SCRHP outfall site in downtown Tucson toward Rillito, AZ, ending just south of Rillito where hydrological conditions shift greatly due to agricultural influences (Figure 3). To provide comparison, I analyzed data from this downstream reach alongside data from an upstream reach of the Santa Cruz River, extending from north of Sahuarita, AZ, to the SCRHP outfall site in Tucson. For both reaches, I also used land cover analysis which included a 30 m buffer on either side of the river's arc hydro centerline as defined by the National Hydrography Dataset from USGS.

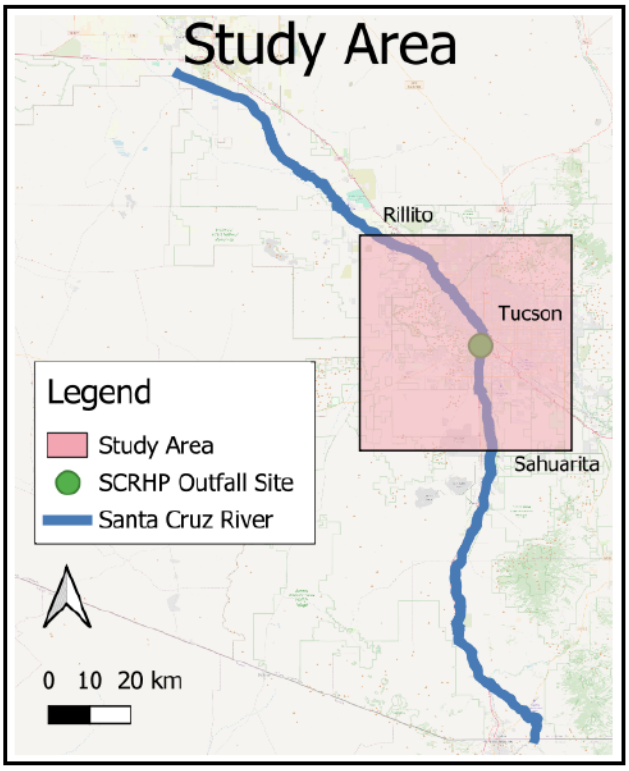


Figure 3. Southcentral Arizona highlighting the section of the Santa Cruz River that is the focus of this study.

Land Cover Classification Data Collection

I collected land cover classification data using GIS-based remote sensing techniques. The primary data source was the USGS National Land Cover Database (NLCD, 2018 & 2023), which provides land cover classification data broken into 30 m^2 pixels. NLCD classifications include including the following categories of land cover; open water, perennial ice/snow, developed open space, developed low intensity, developed medium intensity, developed high intensity, barren land, deciduous forest, evergreen forest, mixed forest, shrub/scrub, grassland/herbaceous, pasture/hay, cultivated crops, woods wetlands, and emergent herbaceous wetlands (Appendix 1).

A mask layer was created to create a boundary around the river channel centerline to define the study area. Pixels extending 30 m, or one pixel, perpendicular to the centerline in each direction were included in the boundary. Within the GIS software, QGIS (v3.36.1), this boundary was used as a mask layer to clip the NLCD 2018 and 2023 layers to isolate the data within the study area. Downstream and upstream reaches were also clipped using a mask layer that extended from the SCRHP outfall site to Rillito, AZ, for the downstream reach and from the Sahuarita, AZ to the SCRHP outfall site for the upstream reach (see Figure 2).

Through the attributes table, individual pixel classification was identified for both downstream and upstream reaches in the 2018 and 2023 datasets. To facilitate analysis, the more specific NLCD land cover classifications were combined into the following broader categories as defined by NLCD MRLC, water (open water and perennial ice/snow), developed (developed open space, developed low intensity, developed medium intensity, and developed high intensity), barren (barren land), forest (deciduous forest, evergreen forest, and mixed forest), shrubland (shrub/scrub), herbaceous (grassland/herbaceous), planted/cultivated (pasture/hay and cultivated crops), and wetlands (woody wetlands and emergent herbaceous wetland).

Image Acquisition

High-resolution imagery was acquired from Google Earth Pro Historical Imagery for spatial land change analysis. High-resolution images, with spatial resolution that allows you to clearly distinguish objects on the ground as fine as 1 m per pixel or better, were obtained for the years 2018 and 2024 at approximately the same time of year (March) to minimize possible variation. The years 2018 and 2024 were selected as the closest available data before the initiation of the SCRHP and the most recently available. This image acquisition was made to supplement NLCD data, visually assess land cover changes, and compare NLCD classification to satellite imagery for verification.

Land Cover Change Data Analysis

Remote sensing techniques were used to analyze land cover change over time. QGIS (v3.36.1) was used to determine specific pixels that changed or remained persistent from 2018 to 2023. Spatial patterns were examined to determine whether changes were concentrated in the downstream or upstream reaches from the SCRHP outfall site.

Individual pixel classifications in 2018 and 2023 were compared for both the downstream and upstream regions to determine which classifications of land cover were changing and what classifications they were transitioning to.

Statistical analyses using R (v.4.4.1) were planned, including a paired t-test to compare land cover classification before and after the initiation of the SCRHP, however, because error in NLCD data could not be quantified, analysis for statistical significance could not be conducted. Additionally, due to the implausibility of the observed changes to land cover, the results were deemed not to be statistically relevant. However, there is still value in a descriptive approach,

which I include below.

RESULTS

Land Cover Change

The area extending 50 m in each direction from the centerline of both the downstream and upstream reaches of the Santa Cruz River from the SCRHP outfall site exhibited land cover classification changes according to NLCD data. The downstream reach area exhibited greater total change of classification following the initiation of SCRHP, with 60.49% of the pixels (294 of the total 486) in the bounded area along the downstream reach of the Santa Cruz River changing land cover classification (Table 1). The area along the upstream reach experienced less total change, with 34.80% of the pixels (65 of the 187 total) changing land cover classification from 2018 to 2023 (Table 1). Areas along both the downstream and upstream reaches did have many pixels that did not experience change, with 39.50 and 65.24% respectively, of the pixels remaining persistent in their land cover classification.

Table 1. Total pixels (30 m^2) along the upstream and downstream reaches of the Santa Cruz River that exhibited a change in land cover classifications or remained persistent from 2018 to 2023.

	Downstream	**Upstream**
Changed Land Cover (Pixels)	294 (60.49%)	65 (34.80%)
Persistent Land Cover (Pixels)	192 (39.50%)	122 (65.24%)

Of the changing land cover classification, the downstream reach saw the greatest net changes in the total amount of developed land cover, which increased by 28 pixels (Table 2). The area along the downstream reach also demonstrated net changes in shrubland with a loss of 11 pixels, planted/cultivated land cover with a loss of 10 pixels, and wetlands with a loss of 7 pixels (Table 2). The area along the upstream reach saw a net loss of 5 pixels for the developed land cover classification and a gain of 5 pixels for the shrubland land cover classification.

Table 2. Net change of land cover classification along the downstream and upstream reaches of the Santa Cruz River from 2018 to 2023.

Land Cover Type	Downstream Gain/Loss (Pixels)	Upstream Gain/Loss (Pixels)
Water	0	0
Developed	+28	-5
Barren	0	0
Forest	0	0
Shrubland	-11	+5
Herbaceous	0	0
Planted / Cultivated	-10	0
Wetlands	-7	0

Land cover classification changed along the downstream reach of the Santa Cruz River from 2018 to 2023 (Table 3). Of the areas exhibiting changing land cover, most of the downstream changes involved transitions from shrubland to developed land (104 pixels) and developed to shrubland (92 pixels), indicating a shift between these land cover types (Table 3). Additionally, small-scale conversions were observed between developed land and wetlands, as well as minor losses in planted/cultivated land (Table 3).

Table 3. Land cover classification transitions in number of pixels changed from 2018 to 2023 along the downstream reach of the Santa Cruz River.

		Land Cover 2023							
		Water	Developed	Barren	Forest	Shrubland	Herbaceous	Planted / Cultivated	Wetlands
Land Cover 2018	Water	**0**	0	0	0	0	0	0	0
	Developed	0	**146**	0	0	92	0	4	14
	Barren	0	0	**0**	0	0	0	0	0
	Forest	0	0	0	**0**	0	0	0	0
	Shrubland	0	104	0	0	**39**	0	2	20
	Herbaceous	0	0	0	0	0	**0**	0	0
	Planted / Cultivated	0	6	0	0	9	0	**1**	1
	Wetlands	0	28	0	0	14	0	0	**6**

When compared to the downstream reach, pixels along the upstream reach exhibited a lower variety of types of land cover transitions (Table 4). The transitions included shrubland converting to developed land (30 pixels) and developed land shifting back to shrubland (35 pixels). No other land cover transitions were observed along the upstream reach (Table 4). Unlike the downstream reach, the upstream region exhibited fewer transitions between multiple land cover classifications.

Table 4. Land cover classification transitions in number of pixels changed from 2018 to 2023 along the upstream reach of the Santa Cruz River.

		Land Cover 2023							
		Water	Developed	Barren	Forest	Shrubland	Herbaceous	Planted / Cultivated	Wetlands
Land Cover 2018	Water	**0**	0	0	0	0	0	0	0
	Developed	0	**103**	0	0	35	0	0	0
	Barren	0	0	**0**	0	0	0	0	0
	Forest	0	0	0	**0**	0	0	0	0
	Shrubland	0	30	0	0	**19**	0	0	0
	Herbaceous	0	0	0	0	0	**0**	0	0
	Planted / Cultivated	0	0	0	0	0	0	**0**	0
	Wetlands	0	0	0	0	0	0	0	**0**

My results included measured changes as observed through available NLCD datasets. Some results may be accurate; others may be inaccurate due to substantial errors in the NLCD data at fine scales (Kleindl et al. 2015). This error and its potential influence on the results are addressed in the discussion section of this study.

According to the NLCD 2019 accuracy assessment, Level II land cover classifications had an overall accuracy (OA) of 77.5 ± 1% when evaluated against primary reference labels (Wickham et al. 2023). However, detecting land cover change, such as transitions from shrubland to wetlands, the database is far less reliable. Users' accuracies (UA), which measures the probability that a pixel classified into a given land cover category actually represents that category on the ground, was generally below 50%, except for forest loss and grass gain, which exceeded 70% (Wickham et al. 2023). Producer's accuracies (PA), which reflects the probability

that a reference pixel for a given land cover type is correctly classified on the map, was also below 50%, apart from water and grass, which were above 70% (Wickham et al. 2023). Accuracy assessments for 2023 datasets are not yet available.

Using confusion matrices provided by USGS (Appendix 3) estimates of land cover change were developed to evaluate classification accuracy of land cover changes observed along the downstream and upstream reaches of the Santa Cruz River between 2018 and 2023 (Table 5 and Table 6). The matrices (Appendix 3) compare mapped land cover classes, from NLCD data to estimated reference classes, accounting for thematic accuracy rates published by USGS (Wickham et al. 2023). Rather than assuming uniform accuracy across all classes, land cover-specific user's accuracy (UA) values were applied. The following UA values were used for the relevant land cover classifications; 88% UA for developed, 45% UA for shrubland, 75% for planted/cultivated, and 60% for wetlands (Wickham et al. 2023). These UA values reflect the probability that a pixel labeled as a given class truly represents that class on the ground.

Pixels classified incorrectly, based on UA estimates, were redistributed into the most likely misclassified classes based on observed transition patterns. For example, the misclassification between developed and shrubland. This approach provides a more realistic estimate of the potential classification errors within the observed land cover changes. Nationally, developed land classification by NLCD shows higher reliability, however, all transitions, especially those involving shrubland and wetlands, must be interpreted cautiously, given their lower classification accuracy in the NLCD product. The NLCD accuracy assessment from 2019 was used as it is the closest available accuracy assessment to both 2018 and 2023 NLCD data that has been published.

Table 5. Estimated land cover classification transitions in number of pixels changed from 2018 to 2023 along the upstream reach of the Santa Cruz River.

Land Cover 2018	Land Cover 2023								
	Water	Developed	Barren	Forest	Shrubland	Herbaceous	Planted / Cultivated	Wetlands	Total Mapped Pixels
Water	**0**	0	0	0	0	0	0	0	0
Developed	0	**128**	0	0	18	0	0	0	146
Barren	0	0	**0**	0	0	0	0	0	0
Forest	0	0	0	**0**	0	0	0	0	0
Shrubland	0	32	0	0	**47**	0	2	20	104
Herbaceous	0	0	0	0	0	**0**	0	0	0
Planted / Cultivated	0	1	0	0	1	0	**1**	1	6
Wetlands	0	4	0	0	7	0	0	**6**	28

Table 6. Estimated land cover classification transitions in number of pixels changed from 2018 to 2023 along the upstream reach of the Santa Cruz River.

Land Cover 2018	Land Cover 2023								
	Water	Developed	Barren	Forest	Shrubland	Herbaceous	Planted / Cultivated	Wetlands	Total Mapped Pixels
Water	**0**	0	0	0	0	0	0	0	0
Developed	0	**121**	0	0	17	0	0	0	138
Barren	0	0	**0**	0	0	0	0	0	0
Forest	0	0	0	**0**	0	0	0	0	0
Shrubland	0	27	0	0	**22**	0	0	0	49
Herbaceous	0	0	0	0	0	**0**	0	0	0
Planted / Cultivated	0	0	0	0	0	0	**0**	0	0
Wetlands	0	0	0	0	0	0	0	**0**	0

High-Resolution Imagery

High-resolution imagery obtained from Google Earth Pro Historical Imagery shows clear changes in land cover from 2018 to 2024 with an increase in forest and developed land over that time in the area immediately surrounding the Santa Cruz River (Figures 4a and 4b).





Figures 4a and 4b. Satellite images of a stretch of the Santa Cruz River, downstream about 1 mile from the SCRHP outfall site. The left image is from February 2018, and the right image is from February 2024. Sourced from Google Earth Pro Historical Imagery.

Another section of the downstream reach of the Santa Cruz River, about 3 miles downstream of the SCRHP outfall site, in 2018 and in 2024 detect an observable gain of vegetation (shrubland and forest cover) in the area along the Santa Cruz River and gains of developed land (Figures 5a and 5b).





Figures 5a and 5b. Satellite images of another stretch of the Santa Cruz River, downstream about 3 miles from the SCRHP outfall site. The left image is from February 2018, and the right image is from February 2024. Sourced from Google Earth Pro Historical Imagery.

DISCUSSION

Interpretation of Results

My study assessed the impacts of the Santa Cruz River Heritage Project (SCRHP) on land cover change, riparian vegetation response, and the effectiveness of GIS-based remote sensing tools in monitoring restoration in an arid river system. The results suggest that land cover along the restored reach has changed notably since the project's initiation, with 60.49% of the pixels along the downstream reach exhibiting transitions compared to 34.80% of the pixels along the upstream reach. However, the extent of riparian vegetation recovery, as measured through coarse-resolution NLCD data, appeared limited, with no notable net gains in wetland or forest cover observed. High-resolution imagery showed localized vegetative greening; however, these changes were not consistently captured by NLCD classifications, likely due to spatial resolution constraints. Early signs of recovery are suggested, however, NLCD-based remote sensing analysis alone proved insufficient for detecting narrow, fine-scale restoration outcomes in this setting. These findings highlight the need to pair remote sensing with finer-scale imagery or ground verification to accurately assess ecological progress.

The higher observed rate of land cover change along the downstream reach suggests that the reintroduction of surface flows from recycled urban water may be influencing land cover, however, the specific types of transitions complicate this interpretation. Notably, the largest transition was from shrubland to developed land (104 pixels), a shift more indicative of urban encroachment than ecological restoration. Misclassification issues were apparent upon review of National Agricultural Imagery Program (NAIP) high-resolution image overlays of NLCD classification data (Figures 8 and 9), which revealed many instances of misclassification. For

example, several areas classified as developed land were more accurately characterized as shrubland.



Figure 6. Image showing National Land Cover Database (NLCD) overlaid National Agriculture Imagery Program (NAIP) high-resolution imagery (2018), highlighting misclassification of some pixels as developed.

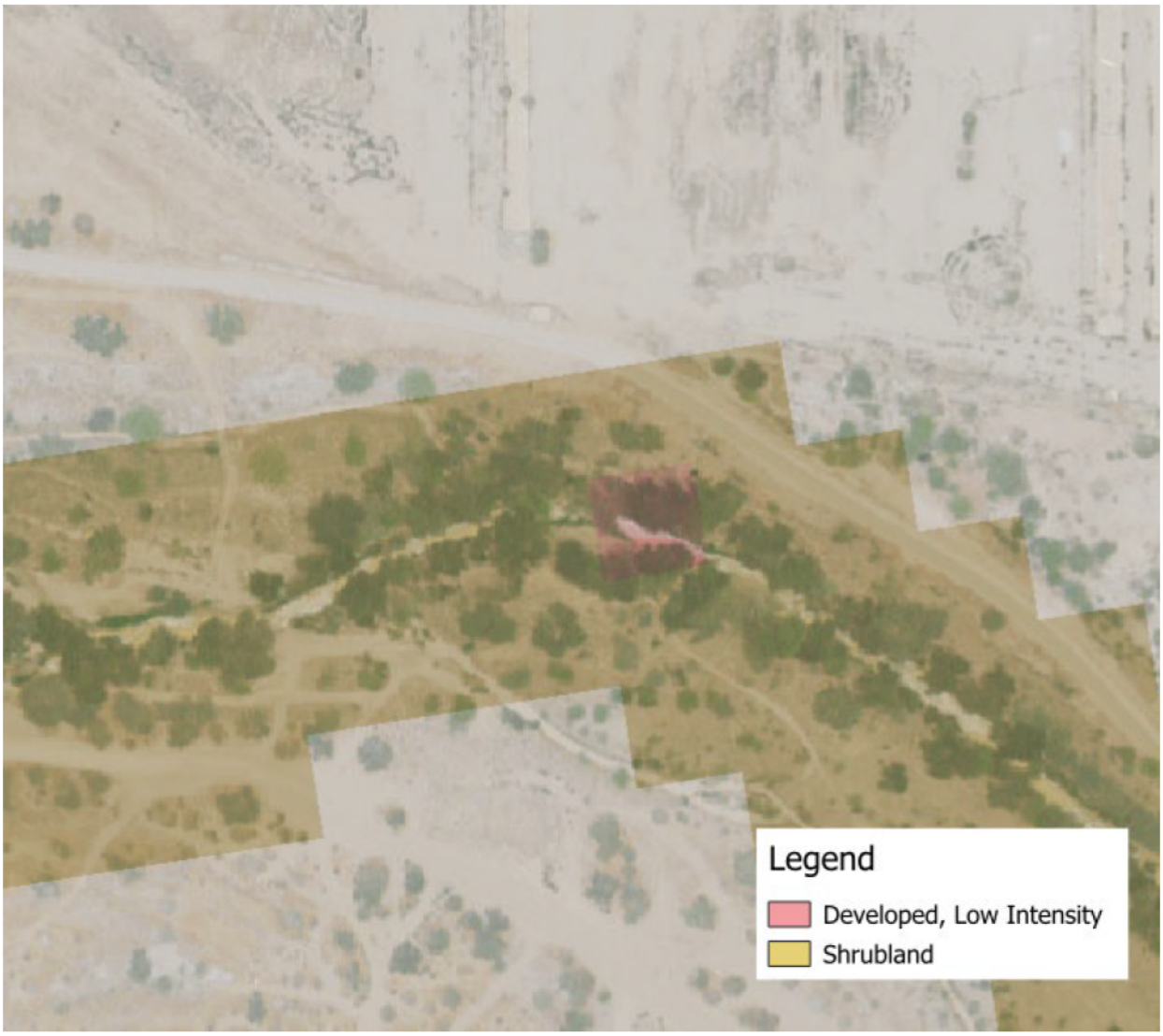


Figure 7. Image showing National Land Cover Database (NLCD) overlaid National Agriculture Imagery Program (NAIP) high-resolution imagery (2018), highlighting misclassified pixel.

The next most common transition was from developed land to shrubland (92 pixels). Although seemingly desirable from an ecological restoration perspective, this transition is unlikely to represent real conversion processes in the context of the SCRHP's reintroduction of recycled urban water. Rather, substantial confusion between developed land cover and shrubland, as indicated in the NLCD confusion matrices (see Tables 6 and 7), suggest that many of these changes reflect classification errors rather than actual landscape dynamics. This

misclassification is supported by the high-resolution NAIP imagery in Figure 6 and Figure 7, where many "developed" pixels in 2018 already show substantial vegetative cover.

Similarly, transitions from developed land cover to wetlands were recorded, but such changes over a four-year period are ecologically implausible without more significant hydrological modification (Vesipa et al. 2016). NAIP imagery of Figure 7 specifically shows a pixel that was classified as developed in 2018 NLCD data, which was subsequently classified as wetlands in 2023 NLCD data. The image suggests misclassification as the reason for the change rather than rapid wetland establishment. Given these patterns, it is important to consider the broader ecological significance of the observed transitions.

Ecological Importance of Land Cover Transitions

The zones along the downstream reach where observed transitions between developed land and shrubland occurred, specifically those pixels that are transitioning to vegetation, may indicate early stages of ecological recovery. However, the observation that net gains in water or wetland land cover were not made indicates that, according to NLCD data alone, riparian ecosystem recovery was not observed.

This lack of a large-scale increase in wetland pixels is important. These observations are not consistent with the expectations of a river restoration project (Vesipa et al. 2016). A plausible interpretation is that while vegetative response to moisture may have occurred, it may not yet be sufficient to reclassify the areas as wetlands under NLCD's classification requirements. This may also reflect the limitations of the 30-meter pixel size and accuracy within NLCD data, where narrow riparian changes may be missed entirely.

To assess whether the observed land cover transitions align with on-the-ground

ecological realities, Google Earth Pro satellite imagery from 2018 and 2024 was reviewed for selected sections of the river. These visual observations show that many areas downstream of the SCRHP outfall site do show an increase in green vegetation (see Figures 4a and 5a). These observations do make ecological sense following the reintroduction of surface flow. However, these observations contradict the net decrease in vegetation and wetland land cover that was observed through NLCD data analysis. This contradiction is likely a result of the major limitations of this study, such as the use of coarse-scale NLCD data with 30 m pixel resolution. NAIP imagery was also used to confirm the classification errors suspected in the NLCD data (see Figures 6 and 7).

Limitations

My conclusions of this study must be interpreted with the consideration of several substantial limitations. Thematic misclassification within NLCD data is a primary concern. A lack of long-term monitoring and ground-truthing also constrained this study.

Thematic misclassification is a major limitation of this study because of known inaccuracies in NLCD's land cover classification. While the NLCD 2019 database reported Level II land cover accuracy of about 77.5% overall, user accuracies for most change classes – such as wetland gain or shrubland loss – were generally below 50% (Wickham et al. 2023). This error rate is likely the cause for the more ecologically implausible results of this study. For example, it may explain how developed land was able to convert to wetlands in such a short period of time, or the seemingly large number of pixels that transitioned between developed to shrubland. Previous studies have also encountered this limitation. A core critique raised by Kleindl et al. (2015) is that remote sensing datasets are frequently incorporated into assessments

without accounting for their classification error, leading to naïve interpretations of ecological patterns .

The 30 m pixel resolution on NLCD can also be inadequate for capturing fine-scale ecological changes typical in narrow riparian systems. A single pixel may contain a complex mosaic of land cover classifications. For example, open water and vegetation may be present within a pixel that is classified as shrubland or barren. This composite of land cover types can lead to misclassification or complete omission of land cover types. This coarse resolution likely underestimates vegetative and open water gains that occur at smaller spatial scales. These limitations are compounded in narrow or geomorphically confined sections of the river, where even ecologically meaningful changes remain undetected or incorrectly classified. These spatial resolution constraints of NLCD data are a major limitation, as they lead to the conclusion of this study to show a lack of restoration success that seems to be clear through high-resolution imagery.

Visual comparisons with high-resolution imagery from Google Earth Pro Historical Imagery confirm these data limitations. Several land cover transitions identified by NLCD, such as shrubland to developed or developed to wetlands, appear to lack ecological plausibility and were not corroborated by imagery review. These discrepancies suggest that some pixel transitions may reflect error rather than true land cover dynamics.

This project did not include supervised classification, Landsat Normalized Difference Vegetation Index (NDVI) greenness indicators, point-based land cover analysis, or field-based validation, further limiting the confidence in the pixel-level results. Google Earth imagery was used to qualitatively assess the plausibility of transitions, though it cannot replace ground truthing in confirming the presence or extent of land cover classes such as mesquite bosques or

riparian wetlands. Models that fail to incorporate known uncertainties can bias ecological assessments, sometimes leading to an overestimation of restoration progress (Kleindl et al. 2015).

Implications

My study offers valuable insight into the use of remote sensing approaches to evaluating the effectiveness of using recycled urban water for ecological restoration in arid river systems. The considerable limitations in using the NLCD dataset, particularly when a narrow area requires fine-scale analysis, to complete land cover change analysis, made the results impractical.

Despite this, high-resolution imagery of the study area did indicate some levels of success of SCRHP, albeit not at scales detectable by remote sensing coarse-resolution data alone. For this reason, the SCRHP represents a promising model for managed restoration in water-scarce regions. Recycled urban water can provide base flow, recharge groundwater, and support riparian vegetation. However, riparian vegetation restoration outcomes often unfold slowly and may not become ecologically impactful until years after flow reintroduction (Vesipa et al. 2016). My study lacked the long-term monitoring that is required to adequately assess ecological restoration (Palmer et al. 2014). Additionally, these restoration outcomes may not be detectable by all monitoring approaches. The broader success of projects like those along the Rio Grande (Landis 2012) and the Los Angeles River (Wolfand et al. 2022) affirms that recycled urban water can facilitate habitat regeneration, benefit wildlife, and enhance community engagement. Yet, as seen with the Santa Cruz River, such success often requires long timeframes, adaptive management, and nuanced monitoring and evaluation systems.

Recommendations

As many major rivers of the arid Southwest face similar challenges, such as the Rio Grande (Holmes et al. 2022) and the Gila River (Woodhouse and Udall 2022), my study can provide several important takeaways for future restoration projects and for researchers working in arid river systems. The most consequential lesson is that coarse-resolution datasets like NLCD, while useful for broad-scale trends, are insufficient on their own to assess restoration outcomes in narrow, dynamic riparian corridors. Fine-scale changes in vegetation or water presence can easily be masked or misclassified, especially when pixels represent heterogeneous land cover types. As a result, the interpretation of restoration success requires a hybrid approach that uses a combination of coarse remote sensing data with higher-resolution imagery, supervised classification, NDVI, and/or point-based land cover analysis. Field validation, even if limited, is important for confirming observed trends and avoiding misinterpretation of land cover transitions that may not be ecologically plausible.

Additionally, my study reinforces the importance of acknowledging and addressing classification errors within remote sensing or GIS-based assessments. Misclassification can drastically skew conclusions, particularly in systems where observed changes are relatively small in spatial extent but ecologically significant. Finally, long-term monitoring that incorporates both remote and field-based indicators is critical. Restoration in arid systems is a slow and nonlinear process, and success may be demonstrated over decades, not four years as I assessed.

REFERENCES CITED

Arizona Department of Water Resources. 2025. Arizona Groundwater Site Inventory (GWSI). Arizona Groundwater Site Inventory Website.

Beechie, T. J., D. A. Sear, J. D. Olden, G. R. Pess, J. M. Buffington, H. Moir, P. Roni, and M. M. Pollock. 2010. Process-based Principles for Restoring River Ecosystems. BioScience 60:209–222.

Betancourt, J. L. 1990. Tucson's Santa Cruz River and the Arroyo Legacy. University of Arizona Department of Geosciences.

Bischel, H. N., J. E. Lawrence, B. J. Halaburka, M. H. Plumlee, A. S. Bawazir, J. P. King, J. E. McCray, V. H. Resh, and R. G. Luthy. 2013. Renewing Urban Streams with Recycled Water for Streamflow Augmentation: Hydrologic, Water Quality, and Ecosystem Services Management. Environmental Engineering Science 30:455–479.

Datry, T., S. T. Larned, and K. Tockner. 2014. Intermittent Rivers: A Challenge for Freshwater Ecology. BioScience 64:229–235.

Dong, Z. Y., Z. M. Wang, D. W. Liu, K. S. Song, L. Li, C. Y. Ren, and M. M. Jia. 2014. Spatial Decision Analysis on Wetlands Restoration in the Lower Reaches of Songhua River (LRSR), Northeast China, Based on Remote Sensing and GIS. International Journal of Environmental Research 8.

Eastoe, C. J., and A. Gu. 2016. Groundwater Depletion Beneath Downtown Tucson, Arizona: A 240-Year Record. Journal of Contemporary Water Research & Education 159:62–77.

Ekka, A., S. Pande, Y. Jiang, and P. V. Der Zaag. 2020. Anthropogenic Modifications and River Ecosystem Services: A Landscape Perspective. Water 12:2706.

Gerhard, M., A. Koussoroplis, M. Raatz, C. Pansch, S. B. Fey, J. Vajedsamiei, M. Calderó-Pascual, D. Cunillera-Montcusí, N. P. D. Juvigny-Khenafou, F. Polazzo, P. K. Thomas, C. C. Symons, M. Beklioğlu, S. A. Berger, R. M. Chefaoui, K. A. Ger, S. Langenheder, J. C. Nejstgaard, R. Ptacnik, and M. Striebel. 2023. Environmental variability in aquatic ecosystems: Avenues for future multifactorial experiments. Limnology and Oceanography Letters 8:247–266.

Gu, F., and W. Liu. 2010. Applications of remote sensing and GIS to the assessment of riparian zones for environmental restoration in agricultural watersheds. Geo-spatial Information Science 13:263–268.

Gurnell, A. 2014. Plants as river system engineers. Earth Surface Processes and Landforms 39:4–25.

Hoang Tu, L., P. Thi Ha, V. Ngoc Quynh Tram, N. Ngoc Thuy, D. Nguyen Dong Phuong, T. Thong Nhat, and N. Kim Loi. 2023. GIS Application in Environmental Management: A Review. VNU Journal of Science: Earth and Environmental Sciences 39.

Hobbs, R. J., S. Arico, J. Aronson, J. S. Baron, P. Bridgewater, V. A. Cramer, P. R. Epstein, J. J. Ewel, C. A. Klink, A. E. Lugo, D. Norton, D. Ojima, D. M. Richardson, E. W. Sanderson, F. Valladares, M. Vilà, R. Zamora, and M. Zobel. 2006. Novel ecosystems: Theoretical and management aspects of the new ecological world order. Global Ecology and Biogeography 15:1–7.

Hobbs, R. J., and V. A. Cramer. 2008. Restoration Ecology: Interventionist Approaches for Restoring and Maintaining Ecosystem Function in the Face of Rapid Environmental Change. Annual Review of Environment and Resources 33:39–61.

Holmes, R. N., A. Mayer, D. S. Gutzler, and L. G. Chavira. 2022. Assessing the Effects of Climate Change on Middle Rio Grande Surface Water Supplies Using a Simple Water Balance Reservoir Model. Earth Interactions 26:168–179.

Jenkins, K. M., and A. J. Boulton. 2007. Detecting impacts and setting restoration targets in arid-zone rivers: Aquatic micro-invertebrate responses to reduced floodplain inundation. Journal of Applied Ecology 44:823–832.

Jiongxin, X. 2004. Effect of Human Activities on Overall Trend of Sedimentation in the Lower Yellow River, China. Environmental Management 33.

Kingsford, R. T. 2000. Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. Austral Ecology 25:109–127.

Kleindl, W. J., S. L. Powell, and F. R. Hauer. 2015. Effect of thematic map misclassification on landscape multi-metric assessment. Environmental Monitoring and Assessment 187:321.

Landis, M. E. 2012. Sustainable Riparian Restoration—The Utilization of Sewage Effluent to Construct Wetlands along the Rio Grande: A String of Pearls Approach to Replenishment. Open Access Theses & Dissertations 1859.

Larned, S. T., T. Datry, D. B. Arscott, and K. Tockner. 2010. Emerging concepts in temporary-river ecology. Freshwater Biology 55:717–738.

Li, B., G. Yang, R. Wan, X. Lai, and P. D. Wagner. 2022a. Impacts of hydrological alteration on ecosystem services changes of a large river-connected lake (Poyang Lake), China. Journal of Environmental Management 310:114750.

Li, P., D. Li, X. Sun, Z. Chu, T. Xia, and B. Zheng. 2022b. Application of Ecological Restoration Technologies for the Improvement of Biodiversity and Ecosystem in the River. Water 14:1402.

Luthy, R. G., D. L. Sedlak, M. H. Plumlee, D. Austin, and V. H. Resh. 2015. Wastewater-effluent-dominated streams as ecosystem-management tools in a drier climate. Frontiers in Ecology and the Environment 13:477–485.

Micklin, P. 2007. The Aral Sea Disaster. Annual Review of Earth and Planetary Sciences 35:47–72.

Olden, J. D., and R. J. Naiman. 2010. Incorporating thermal regimes into environmental flows assessments: Modifying dam operations to restore freshwater ecosystem integrity. Freshwater Biology 55:86–107.

Palmer, M. A., K. L. Hondula, and B. J. Koch. 2014. Ecological Restoration of Streams and Rivers: Shifting Strategies and Shifting Goals. Annual Review of Ecology, Evolution, and Systematics 45:247–269.

Russell, G. D., C. P. Hawkins, and M. P. O'Neill. 2008. The Role of GIS in Selecting Sites for Riparian Restoration Based on Hyderology and Land Use. Restoration Ecology 5:56–68.

Sabater, S., F. Bregoli, V. Acuña, D. Barceló, A. Elosegi, A. Ginebreda, R. Marcé, I. Muñoz, L. Sabater-Liesa, and V. Ferreira. 2018. Effects of human-driven water stress on river ecosystems: A meta-analysis. Scientific Reports 8:11462.

Sabater, S., and K. Tockner. 2009. Effects of Hydrologic Alterations on the Ecological Quality of River Ecosystems. Pages 15–39 *in* S. Sabater and D. Barceló (editors). Water Scarcity in the Mediterranean. Springer Berlin Heidelberg, Berlin, Heidelberg.

Sayer, C. A., E. Fernando, R. R. Jimenez, N. B. W. Macfarlane, G. Rapacciuolo, M. Böhm, T. M. Brooks, T. Contreras-MacBeath, N. A. Cox, I. Harrison, M. Hoffmann, R. Jenkins, K. G. Smith, J.-C. Vié, J. C. Abbott, D. J. Allen, G. R. Allen, V. Barrios, J.-P. Boudot, S. F. Carrizo, P. Charvet, V. Clausnitzer, L. Congiu, K. A. Crandall, N. Cumberlidge, A.

Cuttelod, J. Dalton, A. G. Daniels, S. De Grave, G. De Knijf, K.-D. B. Dijkstra, R. A. Dow, J. Freyhof, N. García, J. Gessner, A. Getahun, C. Gibson, M. J. Gollock, M. I. Grant, A. E. R. Groom, M. P. Hammer, G. A. Hammerson, C. Hilton-Taylor, L. Hodgkinson, R. A. Holland, R. W. Jabado, D. Juffe Bignoli, V. J. Kalkman, B. K. Karimov, J. Kipping, M. Kottelat, P. A. Lalèyè, H. K. Larson, M. Lintermans, F. Lozano, A. Ludwig, T. J. Lyons, L. Máiz-Tomé, S. Molur, H. H. Ng, C. Numa, A. F. Palmer-Newton, C. Pike, H. E. Pippard, C. N. M. Polaz, C. M. Pollock, R. Raghavan, P. S. Rand, T. Ravelomanana, R. E. Reis, C. L. Rigby, J. A. Scott, P. H. Skelton, M. R. Sloat, J. Snoeks, M. L. J. Stiassny, H. H. Tan, Y. Taniguchi, E. B. Thorstad, M. F. Tognelli, A. G. Torres, Y. Torres, D. Tweddle, K. Watanabe, J. R. S. Westrip, E. G. E. Wright, E. Zhang, and W. R. T. Darwall. 2025. One-quarter of freshwater fauna threatened with extinction. Nature 638:138–145.

U.S. Geological Survey. 2025. Water Data for the Nation. U.S. Geological Survey Nation Water Information Systems.

Vesipa, R., C. Camporeale, and L. Ridolfi. 2016. Recovery times of riparian vegetation. Water Resources Research 52:2934–2950.

Vine, M. F., D. Degnan, and C. Hanchette. 1997. Geographic information systems: Their use in environmental epidemiologic research. Environmental Health Perspectives 105:598–605.

Vorosmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. A. Sullivan, C. R. Liermann, and P. M. Davies. 2010. Global threats to human water security and river biodiversity. Nature 467:555–561.

Wang, Y., X. Gu, G. Yang, J. Yao, and N. Liao. 2021. Impacts of climate change and human activities on water resources in the Ebinur Lake Basin, Northwest China. Journal of Arid Land 13:581–598.

Wickham, J., S. V. Stehman, D. G. Sorenson, L. Gass, and J. A. Dewitz. 2023. Thematic accuracy assessment of the NLCD 2019 land cover for the conterminous United States. GIScience & Remote Sensing 60:2181143.

Wildermuth, L. M., and J. L. Conrad. 2023. Monitoring Aquifer-Storage Change from Artificial Recharge with Repeat Microgravity alon Santa Cruz River, Tucson, Arizona, 2019-22. U.S. Geological Survey Scientific Investigation Reports 2023–5115:20.

Wohl, E. 2019. Forgotten Legacies: Understanding and Mitigating Historical Human Alterations of River Corridors. Water Resources Research 55:5181–5201.

Wohl, E., K. Fryirs, R. C. Grabowski, R. R. Morrison, and D. Sear. 2024. Enhancing the natural absorbing capacity of rivers to restore their resilience. BioScience 74:782–796.

Wohl, E., S. N. Lane, and A. C. Wilcox. 2015. The science and practice of river restoration. Water Resources Research 51:5974–5997.

Wolfand, J. M., K. T. Taniguchi-Quan, R. Abdi, E. Gallo, K. Irving, D. Philippus, J. B. Rogers, E. D. Stein, and T. S. Hogue. 2022. Balancing water reuse and ecological support goals in an effluent dominated river. Journal of Hydrology X 15:100124.

Woodhouse, C. A., and B. Udall. 2022. Upper Gila, Salt, and Verde Rivers: Arid Land Rivers in a Changing Climate. Earth Interactions 26:1–14.

Wu, Q., L. Ke, J. Wang, T. M. Pavelsky, G. H. Allen, Y. Sheng, X. Duan, Y. Zhu, J. Wu, L. Wang, K. Liu, T. Chen, W. Zhang, C. Fan, B. Yong, and C. Song. 2023. Satellites reveal hotspots of global river extent change. Nature Communications 14:1587.

APPENDECIES

Appendix 1. The classification system used by National Land Cover Database (NLCD) as modified from the Anderson Land Cover Classification System and the Multi-Resolution Land Characteristics Consortium (MRLC).

Class\ Value	Classification Description
Water	
11	**Open Water**- areas of open water, generally with less than 25% cover of vegetation or soil.
12	**Perennial Ice/Snow**- areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
Developed	
21	**Developed, Open Space**- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
22	**Developed, Low Intensity**- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
23	**Developed, Medium Intensity** -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
24	**Developed High Intensity**-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren	
31	**Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest	
41	**Deciduous Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
42	**Evergreen Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
43	**Mixed Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrubland	
51	**Dwarf Scrub**- Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
52	**Shrub/Scrub**- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Herbaceous	

	71**Grassland/Herbaceous**- areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
	72**Sedge/Herbaceous**- Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
	73**Lichens**- Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
	74**Moss**- Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated	
	81**Pasture/Hay**-areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
	82**Cultivated Crops** -areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands	
	90**Woody Wetlands**- areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
	95**Emergent Herbaceous Wetlands**- Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Appendix 2. Raw Data – Pixel ID and Land Cover Classification in 2018 and 2023. Land Cover Classifications are grouped as follows; 13 = Water (Open Water and Perennial Ice/Snow), 25 = Developed (Open Space, Low Intensity, Medium Intensity, and High Intensity), 44 = Forest (Deciduous, Evergreen, and Mixed), 53 = Shrubland (Shrub/Scrub), 75 = Herbaceous (Grassland/Herbaceous), 83 = Planted/Cultivated (Pasture/Hay and Cultivated Crops), and 96 = Wetlands (Woody and Emergent Herbaceous).

Downstream			Upstream		
Pixel ID	2018 Classification	2023 Classification	Pixel ID	2018 Classification	2023 Classification
1	25	25	1	53	25
2	53	25	2	25	25
3	53	25	3	25	25
4	25	25	4	25	25
5	53	25	5	53	25
6	83	25	6	25	25
7	25	25	7	25	53
8	25	25	8	25	25
9	25	96	9	25	25
10	83	53	10	53	25

11	25	83	11	25	25
12	25	53	12	25	53
13	25	96	13	53	25
14	53	53	14	25	25
15	53	53	15	53	53
16	96	53	16	25	53
17	53	96	17	25	25
18	53	96	18	25	25
19	83	53	19	25	25
20	53	83	20	25	25
21	96	96	21	25	53
22	96	96	22	53	25
23	53	96	23	25	25
24	96	53	24	25	53
25	96	53	25	25	53
26	83	53	26	53	53
27	83	53	27	53	53
28	83	96	28	25	25
29	96	53	29	53	53
30	53	96	30	53	25
31	96	96	31	25	25
32	53	53	32	25	25
33	53	96	33	53	53
34	53	25	34	25	53
35	96	25	35	53	25
36	53	25	36	25	53
37	96	25	37	53	53
38	96	53	38	25	25
39	53	25	39	25	25
40	96	25	40	53	25
41	96	25	41	53	53
42	96	25	42	25	25
43	25	53	43	53	53
44	25	25	44	25	53
45	25	25	45	25	25
46	53	25	46	25	53
47	25	25	47	25	53
48	25	25	48	25	25
49	25	25	49	25	25

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Appendix 3. Level II agreement between NLCD map and reference labels for NLCD 2019. Class codes are in appendix 1 (Wickham et al 2023).

	Reference												
Map	**10**	**20**	**30**	**40**	**50**	**70**	**80**	**90**	**Total**	**UA**	**UAa**	**MB**	**n**
10	**1.6996**	0.0227	0.0037		0.0009	0.0009	0.0031	0.0288	1.7597	97 (2)	100 (0)	−0.0070	154
20		**5.4994**	0.0082	0.1821	0.1399	0.0118	0.1462	0.0211	6.0086	92 (2)	94 (1)	−1.2630	609
30	0.0267	0.0205	**0.6464**	0.0173	0.2106	0.0732	0.0021	0.0129	1.0098	64 (5)	75 (5)	0.2024	156
40		0.4992	0.0661	**22.6611**	0.8776	0.4988	0.2645	0.2271	25.0944	90 (1)	94 (1)	−2.3337	650
50		0.2373	0.0812	1.1055	**18.1278**	2.6022	0.5033		22.6753	80 (2)	91 (2)	1.3757	421
70		0.2138	0.0009	0.6678	1.6320	**9.9189**	1.1259	0.2664	13.8258	72 (3)	88 (2)	0.0925	454
80		0.6873		0.8755	0.2164	0.4988	**20.8839**	0.2338	23.3956	89 (2)	92 (1)	0.1950	419
90	0.0403	0.0914	0.0009	1.9188	0.0945	0.1108	0.2714	**3.7026**	6.2308	59 (4)	65 (4)	1.7379	382
Total	1.7667	7.2716	0.8074	27.4281	21.2996	13.7333	23.2006	4.4929	100.0000				
SE	0.0426	0.3420	0.1144	0.5952	0.6555	0.6424	0.5926	0.3273					
PA	96 (2)	76 (3)	80 (10)	83 (1)	85 (2)	72 (3)	90 (1)	82 (4)					
PAa	98 (1)	83 (3)	83 (9)	88 (1)	95 (1)	87 (2)	93 (1)	90 (4)					
n	150	615	89	760	438	471	478	244					3245